DESIGN OF ZERO-CURRENT SWITCHING DC-DC BUCK CONVERTER

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This project presents a zero-current switching (ZCS) DC-DC buck converter design, simulation and application. The converter control uses with ZCS technique to decrease the switching losses. Comparing to conventional buck converter, resonant buck converter includes a resonant tank equipped with resonant inductor and capacitor. Complete design-oriented mathematical calculations were done for ZCS converter. The converter is simulated in OrCAD Capture CIS software with design parameters. The simulation result show that the switching losses using ZCS technique is less compared to conventional buck converter.

ABSTRAK

Projek ini mempersembahkan rekabentuk pensuisan arus-sifar penukar buck DC-DC, simulasi dan aplikasi. Penukar tersebut dikawal dengan menggunakan teknik pensuisan arus-sifar untuk mengurangkan kehilangan kuasa semasa pensuisan. Jika dibandingkan dengan penukar buck konvensional, penukar resonan buck terdiri daripada resonan inductor dan resonan capacitor. Rekabentuk penuh berasaskan perkiraan matematik telah dijalankan bagi penukar buck. Penukar ini disimulasi dengan menggunakan perisian OrCAD Capture CIS. Keputusan simulasi menunjukkan kehilangan kuasa pensuisan menggunakan teknik pensuisan arus-sifar lebih rendah berbanding dengan penukar buck konvensional.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	DESCRIPTION
DC	Direct Current
AC	Alternating Current
PWM	Pulse Width Modulation
BJT	Bipolar Junctions Transistor
IGBT	Insulated Gate Bipolar Junction
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
ZCS	Zero Current switching
ZVS	Zero Voltage Switching
QR	Quasi-Resonant
QRC	Quasi-Resonant Circuit
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
LC	Inductor Capacitor
V_s	Input Voltage
L_r	Resonant Inductor
C_r	Resonant Capacitor
f_s	Switching Frequency
f_o	Resonant Frequency

V_o	Output Voltage
I_o	Output Current
L_e	Output Ripple Inductor / Filter Inductor
C_f	Output Ripple Capacitor / Filter Capacitor

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CHAPTER 1

INTRODUCTION

1.1 Overview

Advanced in power electronics in the last few decades led not only to improvements in power devices, but also to new concepts in converter topologies and controls. The various converters for different requirements are developed and related technology is studied by scientist to accomplish the research of new converters.

This work focuses on the issues related with the designing of Zero Current Switching (ZCS) buck converter. The work will append ZCS techniques, LC resonant circuits and buck topology. There is major requirement for changing the voltage from one level to another. Buck converters are one of the most important components of the circuit which operates the voltage from the desired level to fixed level.

This report presents the design procedure of a simple buck converter topology with switching resonant element MOSFET. The operating principle of the converter topology is analysed and operating modes are studied. The performance of the ZCS resonant buck converter is recorded and examined for theoretical verification, waveform results and OrCAD Capture CIS simulation.

1.2 Problem Statement

A buck converter is one of the most important and widely DC-DC converters of modern applications. The buck converters using hard switching technique generate higher switching losses and hence the efficiency becomes low. In order to improve the energy efficiency soft-switching techniques have been proposed to reduce the switching power losses across the power devices. By this reason a buck converter with soft switching technique is develop to increase the efficiency of converter.

1.3 Objectives

The designing of ZCS buck converter for USB power adapter application is the aims of this project. To achieve these aims, the objectives of this report are formulated as follow:

i. To propose soft switching buck converter with ZCS for its switch using as simple circuit as possible.
ii. To compute the optimal values of resonant converter by applying the characteristic curve and mathematical calculation from the circuit configuration.
iii. To simulate the ZCS resonant buck converter using OrCAD Capture CIS software.
iv. To analyse the resonant current and voltage waveforms and the switching voltage and current waveforms.
v. To compare the conventional DC-DC buck converter and the proposed soft-switching DC-DC buck converter in terms of switching loss reduction.

Scope of Project

The scopes of work for this project are:

i. Design ZCS resonant buck converter for 5V, 1.5A USB power adapter
ii. Simulation work using OrCAD Capture CIS as platform
iii. Verification of this resonant converter includes switching power losses, resonant current and voltage waveforms and output current and voltage waveforms

1.4 Layout of Project Report

This section outlines the overall structure of the report and provides a brief explanation for each chapter. This project report contained five chapters.

Chapter 2 describes the losses in switching semiconductor switch which are conduction losses and switching losses. Hard-switching is also known as switching losses. The soft-switching converter, its concept and types which includes zero voltage switching (ZVS) and zero current switching (ZCS) devices are explained. This chapter also discussed hard switching converter topology which is buck converter.

Chapter 3 presents the analysis of ZCS buck converter and its schematic diagram. The theoretical waveforms and mode of operation is discussed in detail.

Chapter 4 discusses the simulation results. The ZCS resonant buck converter is evaluated by simulation study using OrCad Capture CIS. For the comparison purpose, the simulation study of buck converter is also presented.

Chapter 5 summarizes the work undertaken. The chapter concludes by suggesting the potential future research that can be performed, based on the project report work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Power electronics converters are implemented with switching devices that turn on and off while power is being converted from one form to another. The power electronic converters fall generally into six categories:

i. Diode rectifier

It converts AC input voltage to a fixed DC output voltage. The input voltage to rectifier could be either single phase or three phases.

ii. AC to DC Converter (Controlled rectifier)

It converts fixed AC input voltage to a variable DC output voltage. The converter may be fed from single phase or three phases.

iii. AC to AC Converter (AC voltage regulator)

It converts a fixed AC input voltage to variable AC output voltage.

iv. DC to DC Converter (DC chopper)

It converts a fixed DC input voltage to variable DC output voltage or vice versa by varying of duty cycle.

v. DC to AC Converter (Inverter)

It converts a fixed DC input voltage to a fixed AC output voltage.

vi. Static switches

There are called as AC static switches or a DC static switch depends on the supply to these switches either AC or DC supply.

Power converters typically consist of semiconductor devices such as transistors and diodes, energy storage elements such as inductors and capacitors, and some sort of controller to regulate the output voltage. Transistor type devices like BJTs (Bipolar Junctions Transistors), MOSFET (Metal Oxide Silicone Field Effect Transistors) and IGBTs (Insulated Gate Bipolar Transistors) are used as switches in power electronic converters. These devices can be operated in higher switching frequencies which help to reduce converter size.

2.2 Literature Review

(Yuang-Shung Lee and Guo-Tian Chen, 2004) presented quasi-resonant converter to achieve the ZCS for reducing the loss of bi-directional converters as shown in Figure 2.1. The results indicate that the switching loss, switching waveform and EMI emission is reduced in the battery charging system with a battery equalizer. The most disadvantage of this topology is the power MOSFETs of the quasi-resonant ZCS converter have not been exactly turned on at the zero current states.

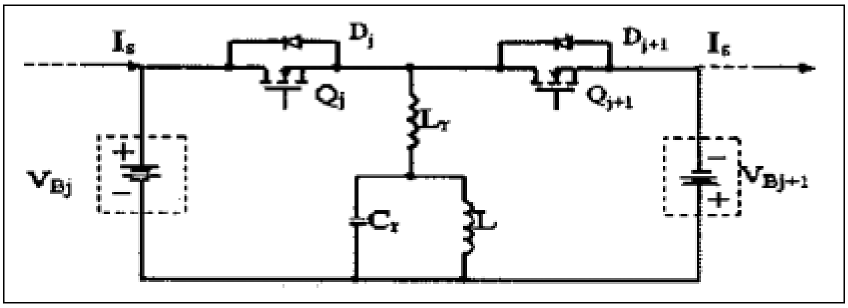


Figure 2.1: Proposed converter in [12]

(Jaroslav Dudrik and Juraj Oetter, 2007) discussed soft switching PWM DC-DC Converters using power MOSFETs and IGBTs in reduction of switching and conduction losses. The circuit configuration of this design is shown in Figure 2.2. An important advantage of the circuit is that the rectifier diodes do not suffer from reverse recovery problem since they commutate with ZCS. The limitation of this topology is soft-switching easy to achieve at light load only.

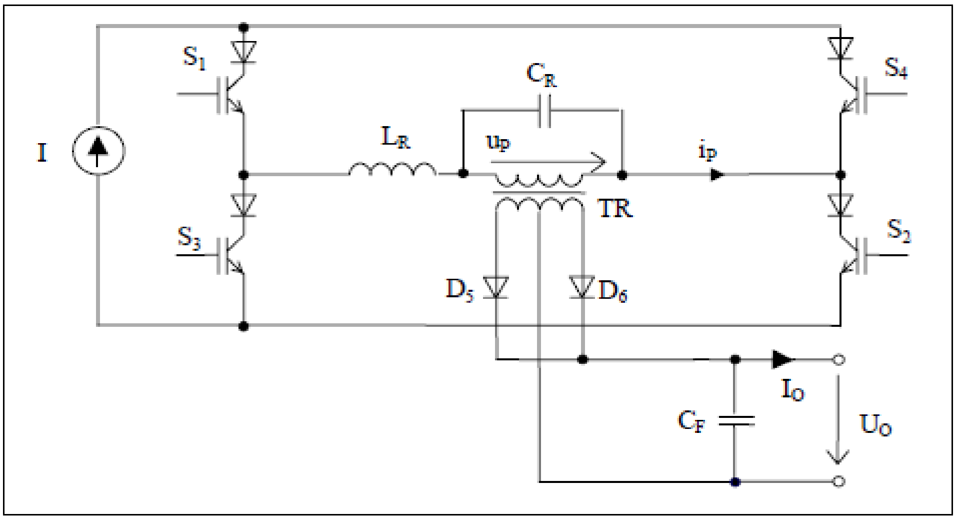


Figure 2.2: Proposed converter in [13]

(Mohammad Mahdavi, Amin Emrani and Hosein Farzanehfard, 2010) proposed a new ZCS resonant buck converter as a soft-switching DC-DC converter using only an auxiliary switch. The circuit configuration of proposed converter is shown in Figure 2.3. The proposed converter both switches are turned on or off under ZCS condition. The most disadvantage of the topology is limitation only suitable for employing IGBT for high power.

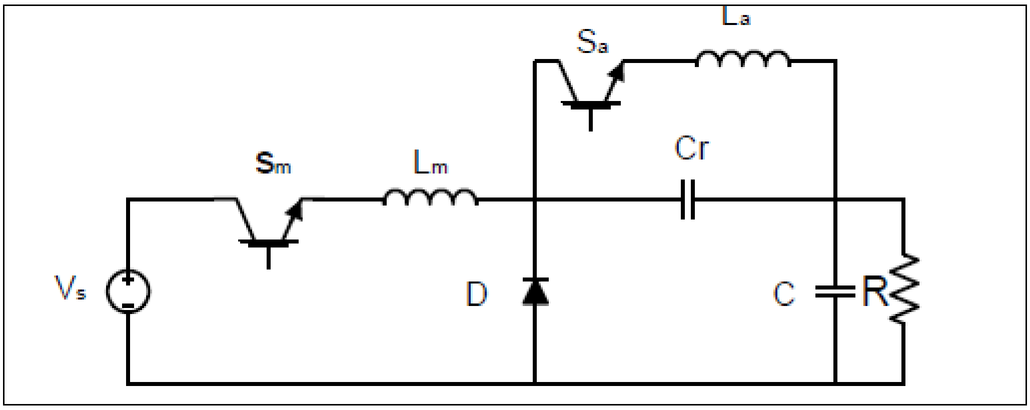


Figure 2.3: Proposed converter in [14]

(P.Preethi and R.Mahalakashmi, 2011) presented a concept which combines the resonant converters and switched-capacitor converters to reduce switching losses. A switched capacitor is used for resonant inverting wherein negative voltage is required. The main disadvantages of the topology is required a large number components which are two switches, some diodes and a number of switching capacitor cells as shown in Figure 2.4.

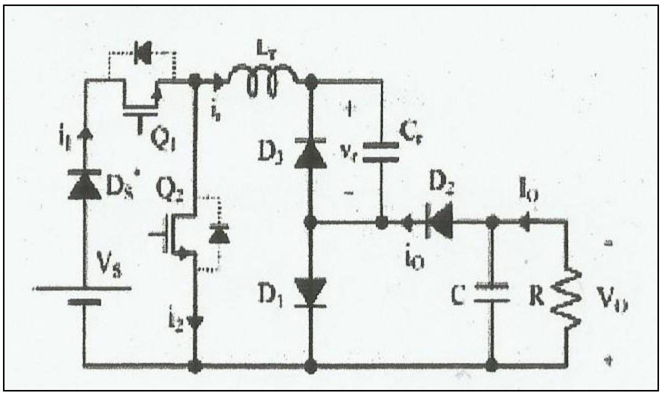


Figure 2.4: Proposed converter in [15]

(Parul Pradhan, 2012) proposed a buck converter topology with resonant configuration as shown in Figure 2.5. ZCS topology is used to diminish the switching losses in enhanced efficiency of converter. This topology is successfully done to minimize switching losses across the device, lower the current and voltage stresses formed across it and diminish the overall size of device with enhanced efficiency for use in high frequency circuits. The problem of this topology is effect of parasitic capacitance in a MOSFET that can instigate conduction without any pulse applied to its gate.

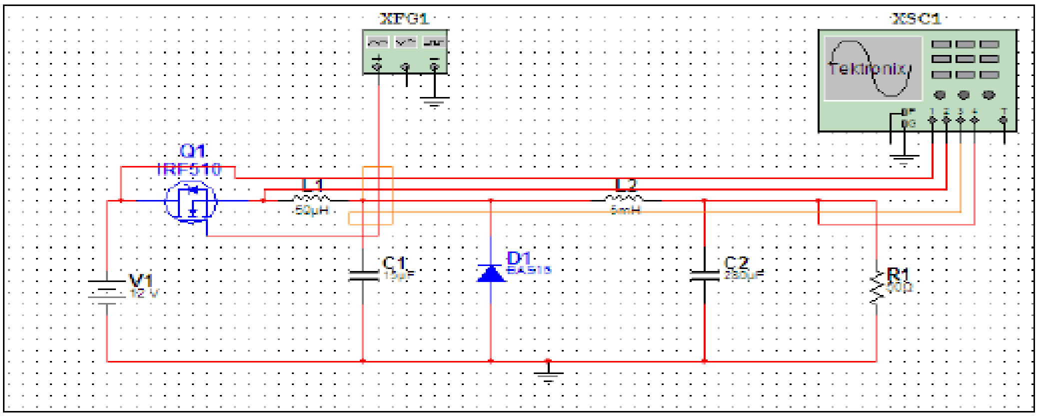


Figure 2.5: Proposed converter in [16]

(José F. da Rocha, Marcelino Bicho dos Santos and José Manuel F.Dores Costa, 2013) presented a QR-ZCS topology to overcome voltage spikes during the switches commutation in a buck converter. The circuit configuration of this converter is shown in Figure 2.6. Results show that resonant DC-DC converters generate voltage spikes which magnitude are sometimes higher than that generated in a hard switching converter and are superimposed to the overvoltage occurring in the resonant phase. The voltage spikes generated in DC-DC converters can cause circuit malfunctions or device breakdown hence gives low energy efficiency. Therefore, this topology is not considered for this project.

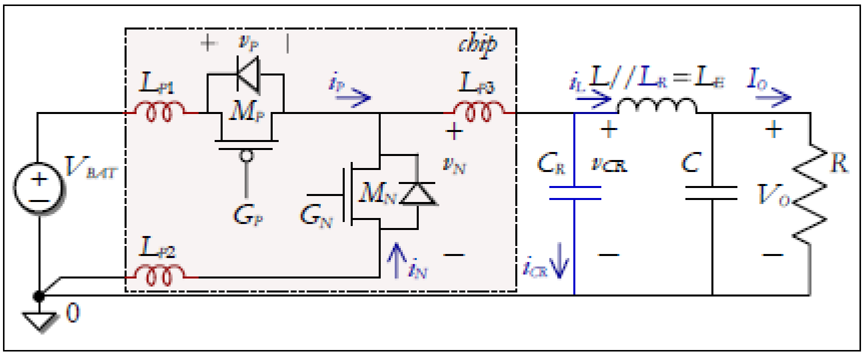


Figure 2.6: Proposed converter in [17]

(G. Yanik and E.Isen, 2013) proposed a 60W full wave quasi-resonant zero-current switching buck converter to decrease the switching losses. The result states that the switching loss is zero. Therefore this topology is considered for this project. The circuit configuration of this proposed converter is shown in Figure 2.7.

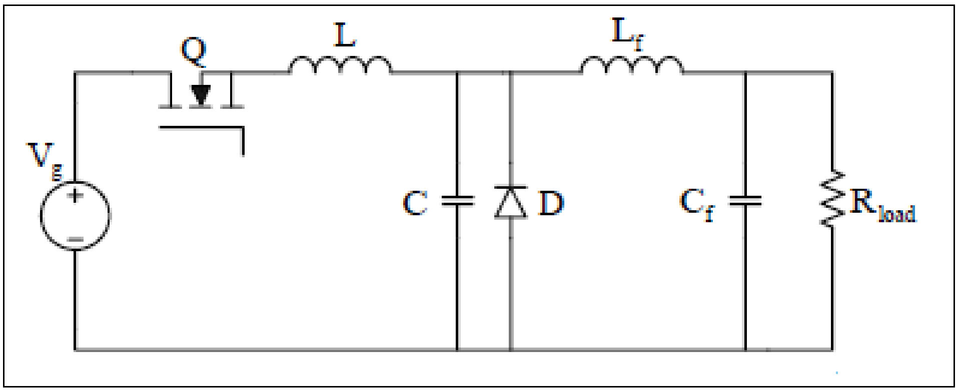


Figure 2.7: Proposed converter in [1]

2.3 DC-DC Converter

DC-DC converter converts a fixed DC input voltage to variable DC output voltage or vice versa by varying of duty cycle. There are many types of DC-DC converter such as buck converter, boost converter, buck-boost converter and cuk converter. This project focused on buck converter.

2.3.1 Buck Converters

A buck converter is a step-down DC to DC converter that uses a switching device, a diode, an inductor and a capacitor as shown in Figure 2.8. Typical waveforms are shown in Figure 2.2 under assumption that the inductor current is always positive. The state of the converter in which the inductor current is never zero for any period of time is called the continuous conduction mode (CCM). It can be seen from the circuit that when switch *S* is commanded to the on state, the diode *D* is reverse biased. When the switch *S* is off, the diode conducts to support an uninterrupted current in the inductor.

The DC-DC converters can operate in two distinct modes with respect to the inductor current, i_L. Figure 2.9 depicts the CCM in which the inductor currents always greater than zero. When the average value of the input current is low (high *R*) and/or the switching frequency f_s is low, the converter may enter the discontinuous conduction mode (DCM). In the DCM, the inductor current is zero during a portion of the switching period.

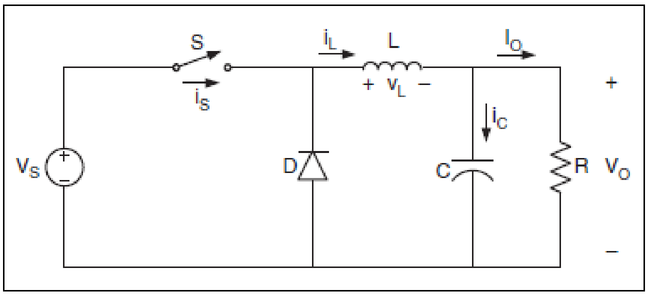


Figure 2.8: Buck converter

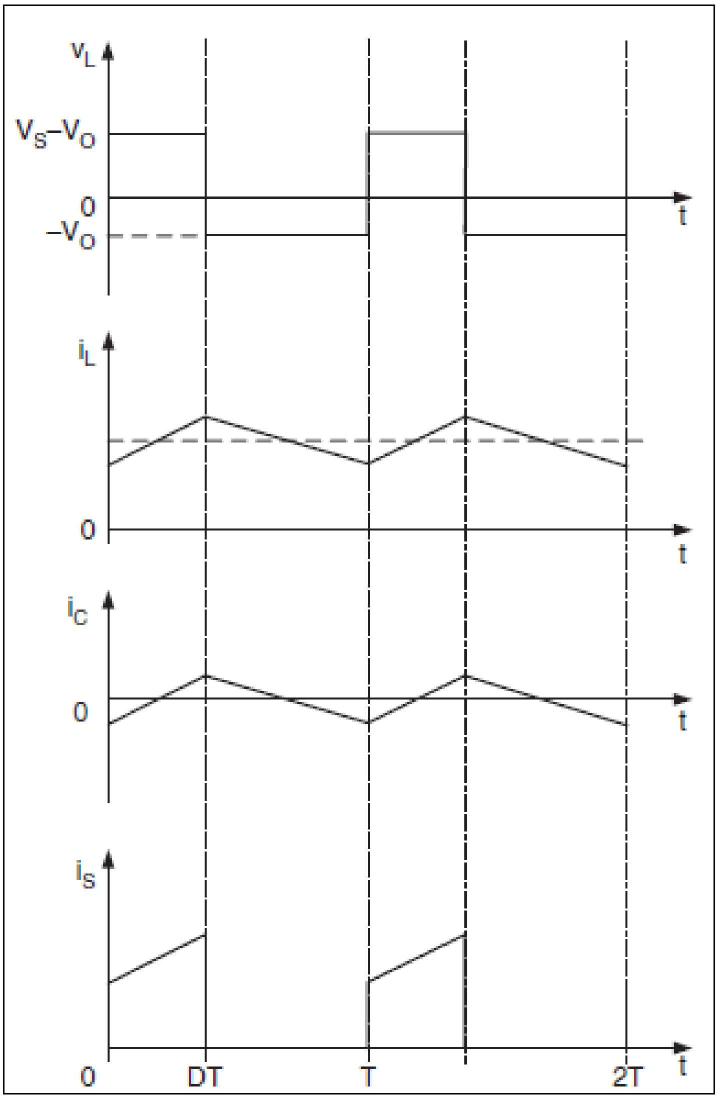


Figure 2.9: Buck converter waveforms

The key parameters that involved in buck converter design are discussed as follows.

The output voltage V_o is expressed as

$$V_o = DV_s \tag{2.1}$$

where D is the duty cycle.

The minimum value of inductance $L_{\min}$ required for continuous current is

$$L_{\min} = \frac{(1-D)R}{2f} \tag{2.2}$$

For $L > L_{\min}$ the converter operates in the CCM.

The value of filter inductance L for continuous-current as

$$L = \left(\frac{V_s - V_o}{\Delta i_L f} \right) D = \frac{V_o \left(1 - D\right)}{\Delta i_L f} \tag{2.3}$$

where Δi_L is the peak-to-peak ripple current in the inductor

The minimum value of capacitance $C_{\min}$ required for continuous current is

$$C_{\min} = \frac{1 - D}{16 L f^2} \tag{2.4}$$

The value of filter capacitance C for continuous-current as

$$C = \frac{1 - D}{8L \left(\Delta V_o / V_o \right) f^2} \tag{2.5}$$

where ΔV_o is the peak-to-peak ripple voltage at the output

2.4 Power Semiconductor Switching Devices

When semiconductor is used as switch it is possible to control large amounts of load power with relatively low power dissipation. In an ideal case, there will be no power dissipation in the switching device. In a DC-DC converter, an input voltage and the average output voltage is controlled by controlling the switch on and off durations. Normally BJTs, MOSFETs and IGBTs are used as switching devices in DC-DC converters.

BJTs are current-controlled devices, they has largely been replaced by MOSFETs and IGBTs where need to be turned on and off at very high frequencies in the kHz range. A MOSFET is a voltage-controlled device that requires only a small input current. They have a very fast switching speed and low switching losses compared to BJTs. An IGBT combined the advantages of BJTs and MOSFETs. An IGBT is a voltage-controlled device similar to MOSFET which turns on like a MOSFET and conducts like a BJT in saturation. An IGBT is faster than a BJT and slower than a MOSFET.

MOSFETs are used in low power applications (typically a few kilowatts) and have lower current and voltage ratings (typically a few hundreds of volts) but higher frequency well in a range of hundreds of kHz. IGBTs are used in in medium- power applications such as DC and ac motor drives, power supplies, solid-state relays and contactors. They have high voltage and current ratings, but operate in lower frequencies (up to 20kHz).

The summary of this switching characteristics are shown in Table 2.1. Here we are opting for MOSFET because its capability in handling very high frequencies and low switching loss. Diagrams of an N-channel MOSFET are shown in Figure 2.10.

Table 2.1: Switching Characteristics of Power Semiconductors

Device	Power Capability	Switching Speed
BJT	Medium	Medium
MOSFET	Low	Very High
IGBT	Medium	Medium

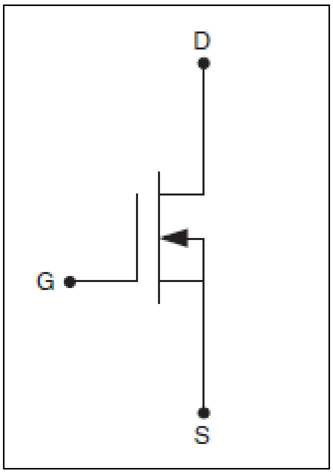


Figure 2.10: Diagram of a power MOSFET

2.5 MOSFET Losses

The semiconductor switches used in power converters are not ideal and are a source of energy losses. The main losses that are related with these switches are conduction losses and switches losses. The magnitude of conduction and switching losses are all dependent on the application and device technology used, but even the smallest loss is undesirable as it reduces the efficiency of the system.

2.5.1 Conduction Losses

The conduction losses in MOSFETS are due its behaving as a resistor when it is in the ON state where the resistance is equal to $R_{DS(ON)}$, the resistance between drain and source. So the power dissipation is equal to $I_D^{\,2} \times R_{DS(ON)}$. The on-state resistance is an important data sheet parameter, since it determines the forward voltage drop across the device and its total power losses.

2.5.2 Switching Losses

In MOSFETs, the main switching losses are caused by the charging and discharging of the gate-to-source and gate-to-drain parasitic capacitance to turn on and off the device respectively. Figure 2.11 shows the physical representation of these capacitors. The MOSFET parasitic capacitance are given in terms of the device data sheet parameters C_{iss} , C_{oss} and C_{rss} as follows.

$$C_{gd} = C_{rss}$$

$$C_{gs} = C_{iss} - C_{rss}$$

$$C_{ds} = C_{oss} - C_{rss}$$

where C_{rss} = small-signal reverse transfer capacitance

C_{iss} = small-signal input capacitance with the drain and source terminals are shorted

C_{oss} = small-signal output capacitance with the gate and source terminals are shorted

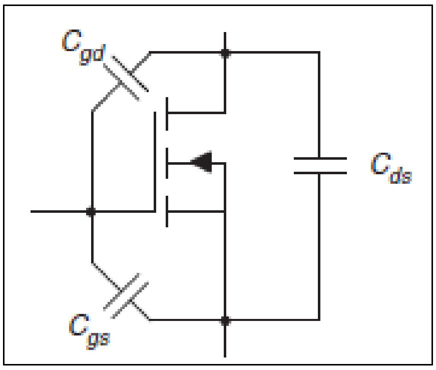


Figure 2.11: Equivalent MOSFET representation including junction capacitances

2.6 Hard-Switching Topologies

In a real semiconductor switch, the switch voltage or switch current do not go to zero instantaneously at the instant of turn-on or turn-off. There is duration of time during any switching transition (either switch turn-on or turn-off) when there is both voltage across and current through the switch. The corresponding power loss during each switching instant is the overlapped area of the switch current and voltage waveform at the instant of turn-on or turn-off of the switch. As the switching frequency increases, these transitions occur more often and the average power loss in device increases. Turning on and turning off the power electronic switches with switching losses is known as “hard switching”.

Figure 2.12 shows the switching transient of the switch in a hard-switched circuit. Clearly shown is the point during the switching transient both the voltage and current have significant values where gives the greatest losses.

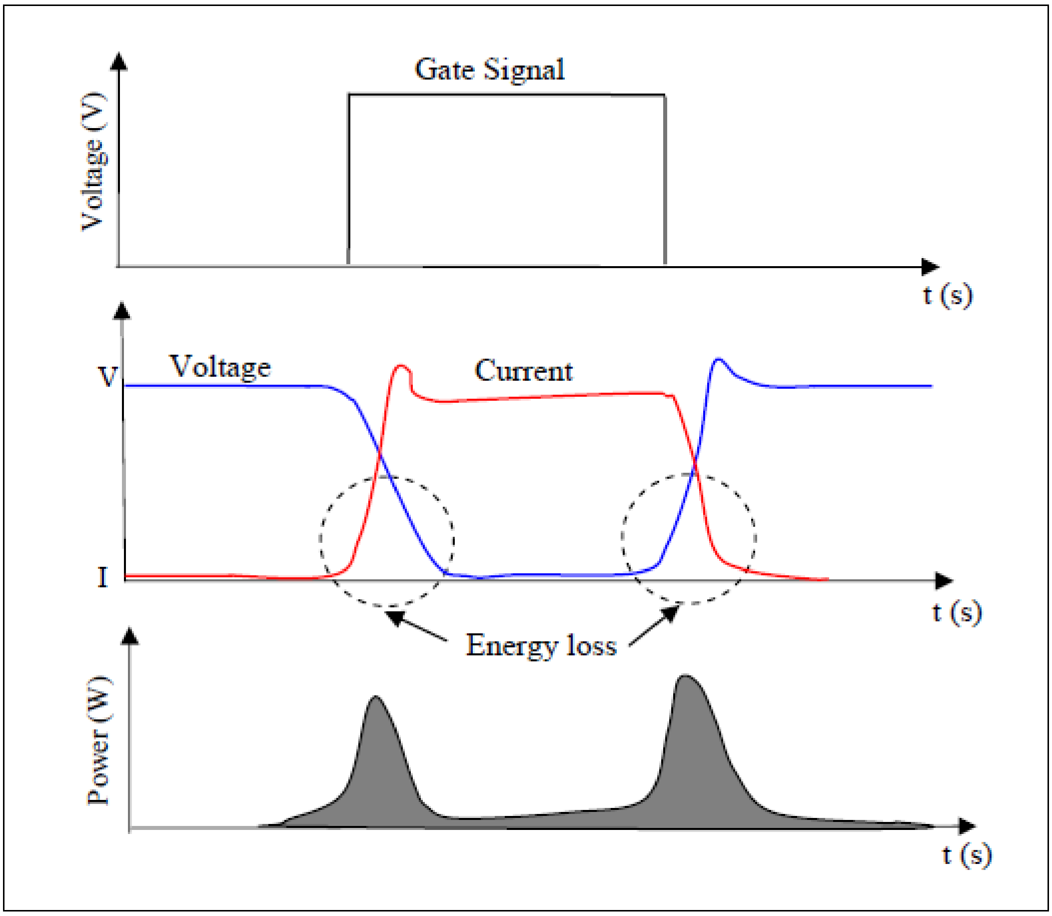


Figure 2.12 Loss of power during hard-switching

2.7 Soft-Switching Topologies

Soft switching techniques force the voltage or current to be zero during the time of transition; therefore there is no overlap between voltage and current and (ideally) no switching loss. Hence, the problem of switching losses and EMI due to hard switching converter operation is overcome by using soft switching. Size and weight of the device is reduced as the heat sink not required. There are two types of soft switching which are zero-voltage switching (ZVS) and zero-current switching (ZCS). There are many ZVS and ZCS techniques have been published. The selection of switching technique is important when dealing with high power converter.

Figure 2.13 shows the switching transient of the switch in a soft-switched circuit. Clearly shown the amount of switching losses is less than the amount of switching losses in Figure 2.12.

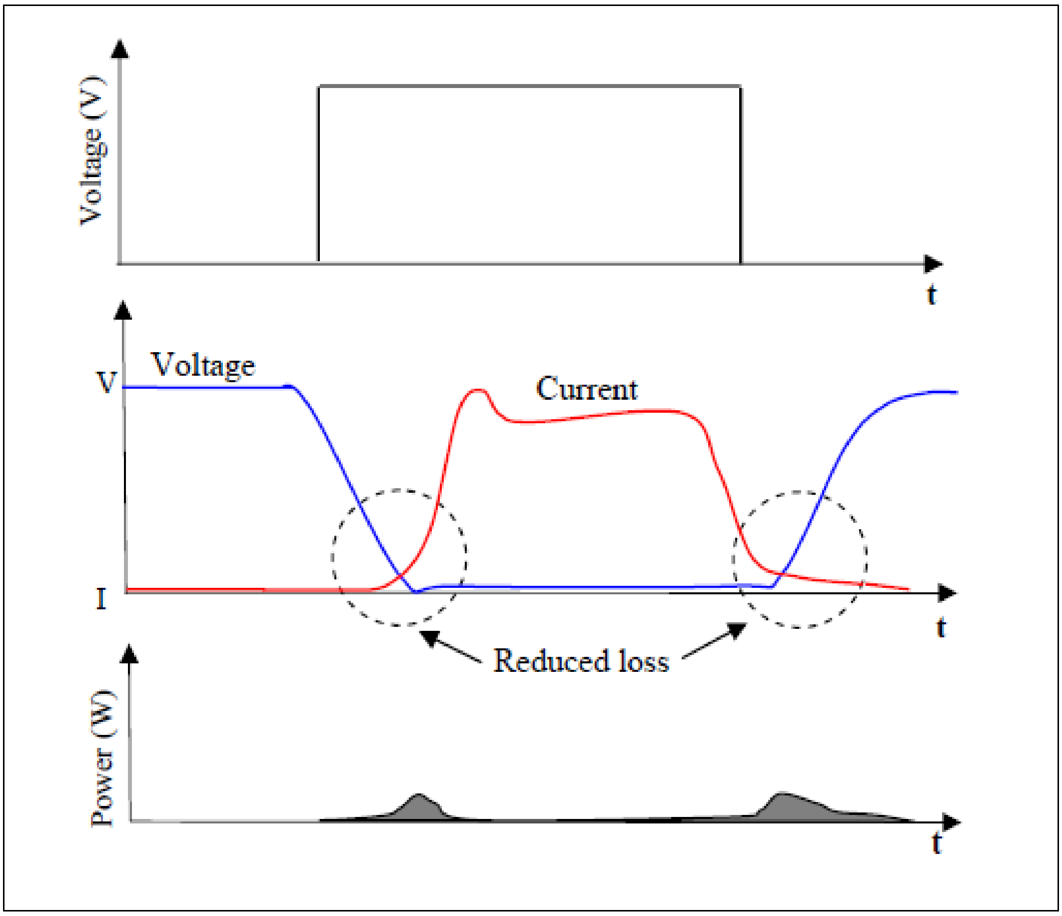
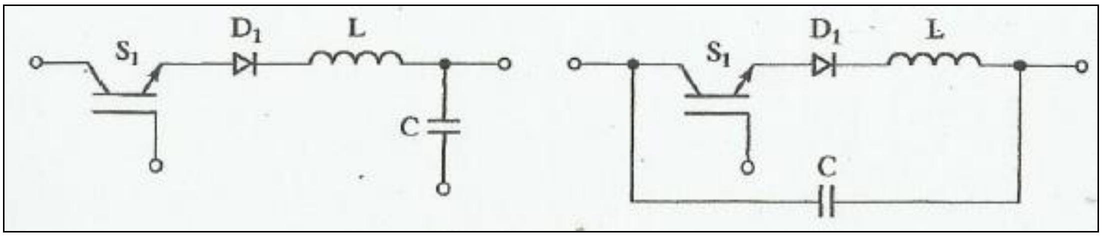


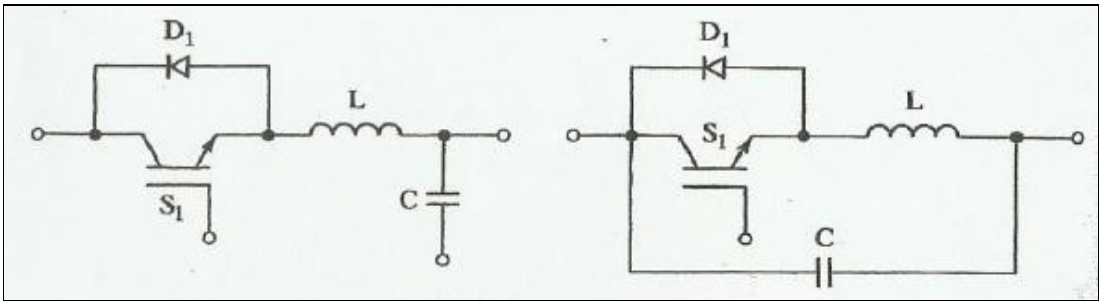
Figure 2.13: Loss of power during soft-switching

2.7.1 Zero Current Switching Resonant Converters

In a zero current resonant, an inductor L_r is connected in series with a power switch S order to achieve ZCS. If the switch S is a unidirectional switch (Figure 2.14a), the switch current is allowed to resonate in the positive half cycle only. The resonant switch is said to be operate in *half-wave* mode. If a diode is connected anti-parallel with the unidirectional switch (Figure 2.14b), the switch current can flow in both directions. In this case, the resonant switch can operate in *full-wave* mode. At turn-on, the switch current will rise slowly from zero. It will then oscillate, because the resonance between L_r and C_r . Finally, the switch can be commutated at the next zero current duration. The objective of this type of switch is to shape the switch current waveform during the conduction time in order to create a zero-current condition for the switch to turn off.



(a) Half-wave types

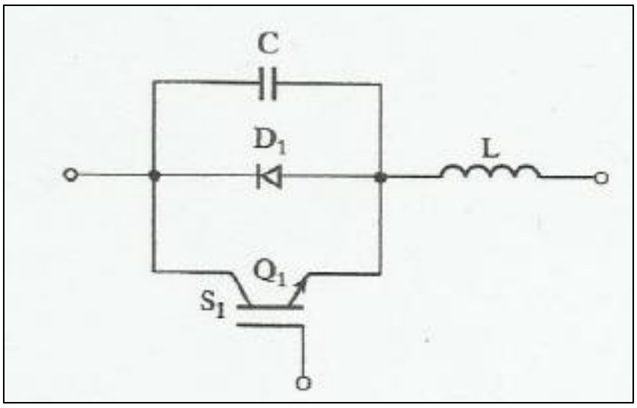


(b) Full-wave types

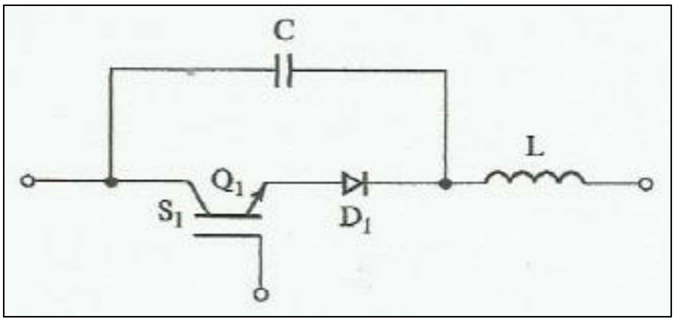
Figure 2.14: Switch configuration for ZCS resonant converters

2.7.2 Zero Voltage Switching Resonant Converters

In a zero voltage resonant, a capacitor C_r is connected in parallel with the switch S for achieving ZVS. If the switch is unidirectional switch (Figure 2.15a) the voltage across the capacitor can oscillate freely in both positive and negative half-cycle. Thus, the resonant switch can operate in *full-wave* mode. If a diode is connected anti parallel with the unidirectional switch (Figure 2.15b), the resonant capacitor voltage is clamped by the diode to zero during the negative half-cycle. The resonant switch will operate in *half-wave* mode. The objective of a zero-voltage switch is to use the resonant circuit to shape the switch voltage waveform during the off-time in order to create a zero-voltage condition to turn on.



(a) Half-wave types



(b) Full-wave types

Figure 2.15: Switch configuration for ZVS resonant converters

2.8 Quasi-resonant Zero Current Switching Converters

Quasi-resonant converters (QRCs) can be considered as a hybrid of resonant and PWM converters. The underlying principle is to replace the power switch in PWM converters with the resonant switch. A large family of conventional converter circuits can be transformed into their resonant converter counterparts. The switch current is forced to oscillate in a quasi-sinusoidal manner, so that ZCS can be achieved. QRCs can be performed as *half-wave* and *full-wave*.

2.8.1 Quasi-Resonant Half-wave Zero-current Switching

A ZCS-QRS designed for *half-wave* operation is shown with a buck type DC-DC converter. The schematic is shown in Figure 2.16. It is formed by replacing the power switch in conventional PWM buck converter with the zero-current resonant switch in Figure 2.14a. The circuit waveforms in steady state are shown in Figure 2.17a. The output filter inductor L_f is sufficiently large so that its current is approximately constant. Prior to the tuning the switch on, the output current I_o freewheels through the output diode D_f. The resonant capacitor voltage V_{cr} equals to zero. At t_0 the switch is turned on with ZCS. A quasi-sinusoidal current I_s flows through L_r and C_r, the output filter and the load. S is then softly commutated at t_1 with ZCS again. During and after gate pulse, the resonant capacitor voltage V_{cr} rises and then decays at a rate depending on the output current. Output voltage regulation is achieved by controlling the switching frequency. Operation and characteristics of the converter depend mainly on the design of the resonant circuit.

It can be seen from the waveform if $I_o > V_i / Z_r$, I_s will not come back to zero naturally and the switch will have to forced off, thus resulting in turn-off losses. The following parameters are defined: voltage conversion ratio M, characteristic impedance Z_r, resonant frequency f_r, normalized load resistance r, normalized switching frequency γ.

$$M = \frac{V_o}{V_{in}} \tag{2.5}$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \tag{2.6}$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2.7}$$

$$r = \frac{R_L}{Z_r} \tag{2.8}$$

$$\gamma = \frac{f_s}{f_r} \tag{2.9}$$

The relationship between M and γ are shown in Figure 2.17b. It can be seen that M is sensitive to the load variation. At light load conditions, the unused energy is stored in C_r leading to an increase in the output voltage. Thus, the switching frequency has to be controlled, in order to regulate the output voltage.

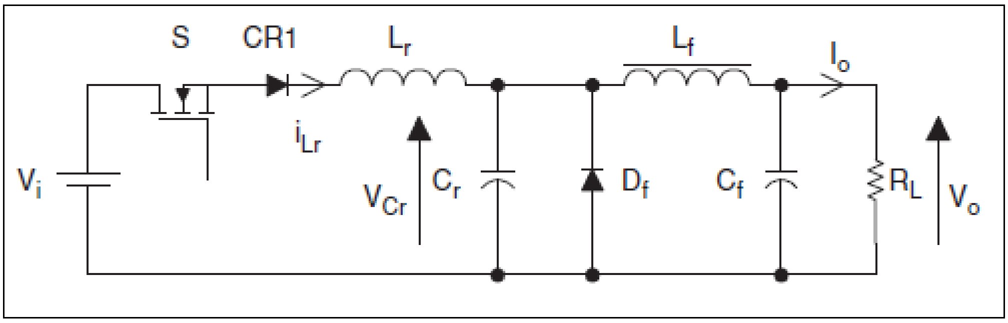
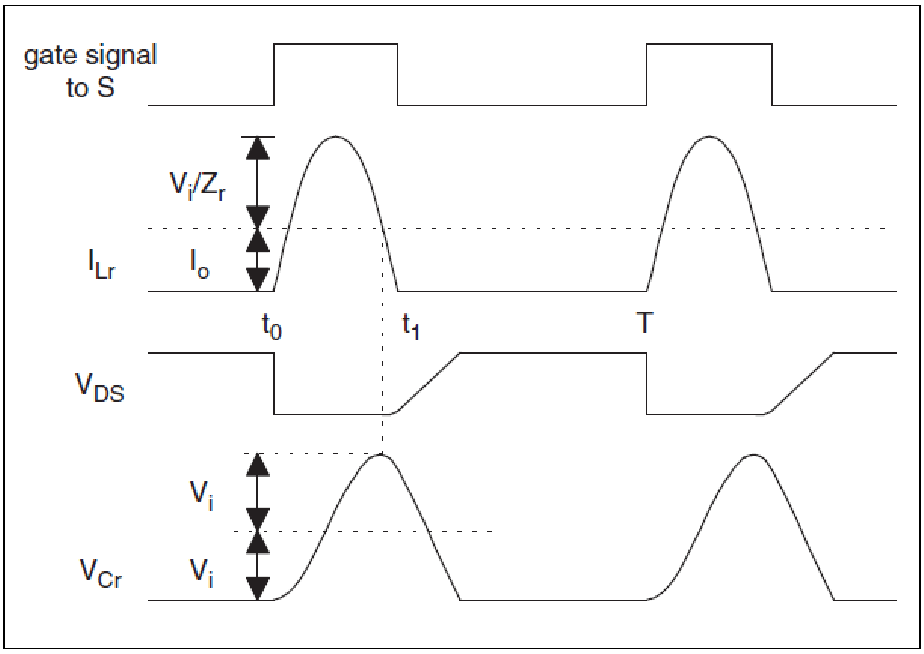
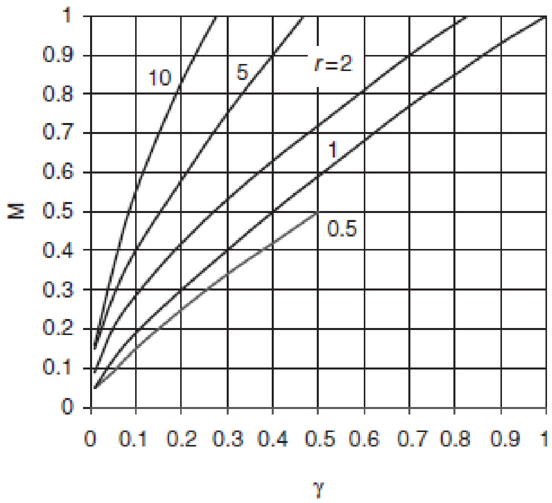


Figure 2.16: Quasi-resonant half-wave ZCS buck converter



(a)



(b)

Figure 2.17: Quasi-resonant half-wave ZCS buck converter: (a) circuit waveforms; (b) relationship between M and γ

2.8.1 Quasi-Resonant Full-wave Zero-current Switching

If anti-parallel diode is connected across the switch, the converter will be operating in full-wave mode. The circuit schematic is shown in Figure 2.18. The circuit waveforms in steady state are shown in Figure 2.19a. The operation is similar to the one in half-wave mode. However, the inductor current is allowed to reverse through the anti-parallel diode and the duration for the resonant stage is lengthened. This permits excess energy in the resonant circuit at light loads to be transferred back to the voltage source, V_i . This significantly reduces the dependence of V_o on the output load. The relationships between M and γ at different r are shown in Figure 2.19b. It can be seen that M is insensitive to load variation.

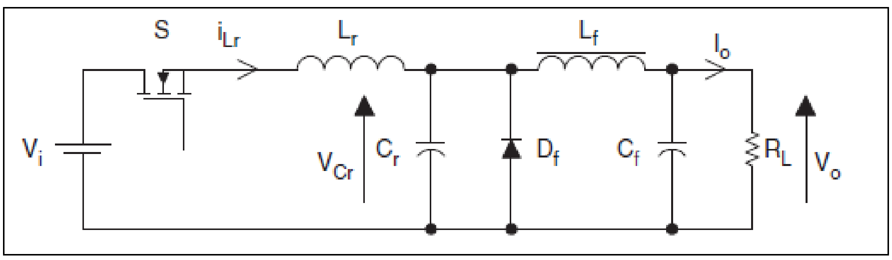
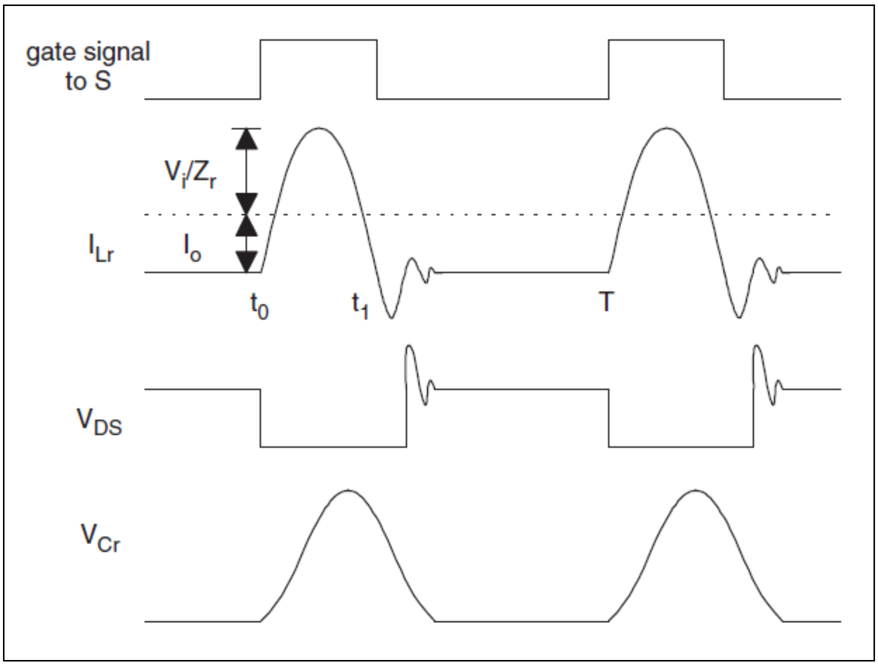
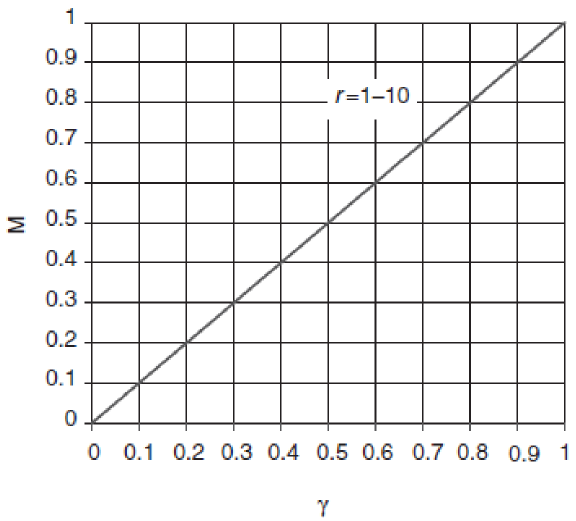


Figure 2.18: Quasi-resonant full-wave ZCS buck converter



(a)



(b)

Figure 2.19: Quasi-resonant half-wave ZCS buck converter: (a) circuit waveforms; (b) relationship between M and γ

CHAPTER 3

METHODOLOGY

3.1 Introduction

In ZCS, it is the current transient which forced to zero before the power device is switched. Under this state, the switch is able to turn off without current flowing through it. Therefore, the current and voltage overlap is overcome by ensuring that the switch current is zero before the voltage rises which leads to the power losses. This method is particularly useful in circuit that utilise bipolar as the main switch. However, ZCS use is not limited to bipolar device as all semiconductor switch technologies can give benefit from the transient; resulting in significantly reduced switching losses.

Typically, to induce zero current transient an inductor is allowed to resonate with a capacitor to create sinusoidal currents. The switching device is turned off when the current grows to zero-point transition.

3.2 The Proposed Converter

The proposed converter is shown in Figure 3.1 for resolving switching losses. The switches of ZCS converter to turn on and off at zero current due to the current produced by a resonant inductor and resonant capacitor (LC resonant circuit) flows through the switch. The resonant circuit consists of switch S_1, inductor L and a capacitor C. The LC circuit is used to stored and transfer energy from input to output in similar manner to the resonant converter. To achieve ZCS, the inductor L is connected in series with power switch S_1. C is connected across the main power diode. When switch current is zero, there is a current flowing through the internal capacitance due to finite slope of the switch voltage at turn-off. This current flow causes the power dissipation in the switch. In ZCS techniques, the turn-off losing of switching devices is almost eradicated.

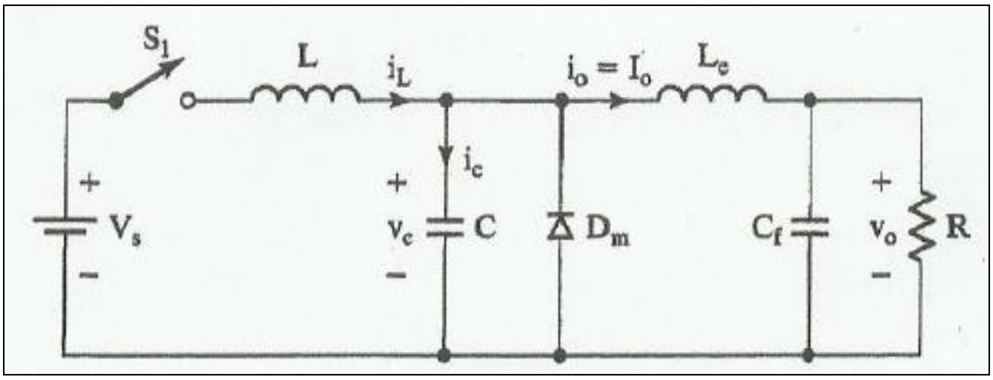


Figure 3.1: ZCS Resonant Buck Converter

3.3 Converter Features

The proposed ZCS buck converter for USB power adapter 5V, 1.5 A is presented. The converter features were listed in Table 3.1.

Table 3.1: Converter Features

Input voltage	12V
Output voltage	5V
Output current	1.5A
Switching frequency	200kHz
Duty cycle	0.4167

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